



## Design of monopiles for multi-megawatt wind turbines at 50 m water depth

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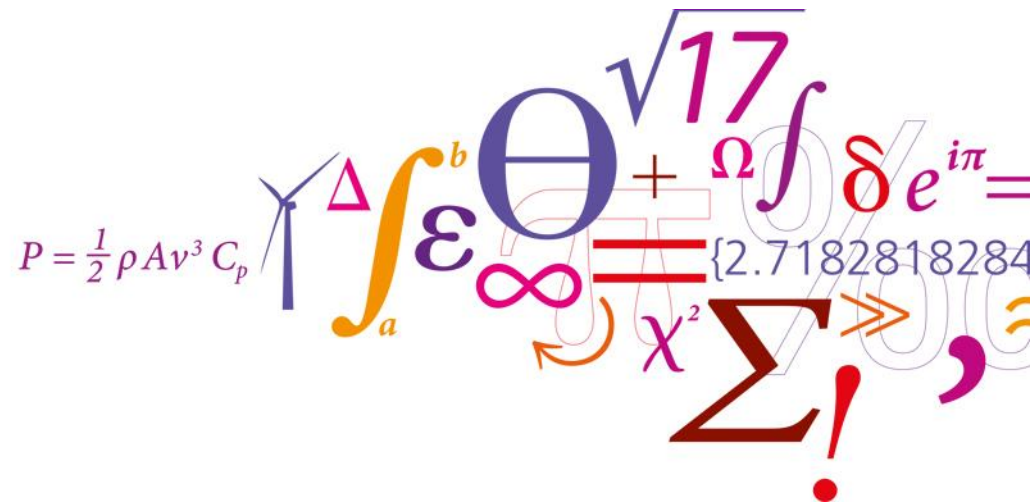
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# Design of monopiles for multi-megawatt wind turbines at 50 m water depth

## Authorship:

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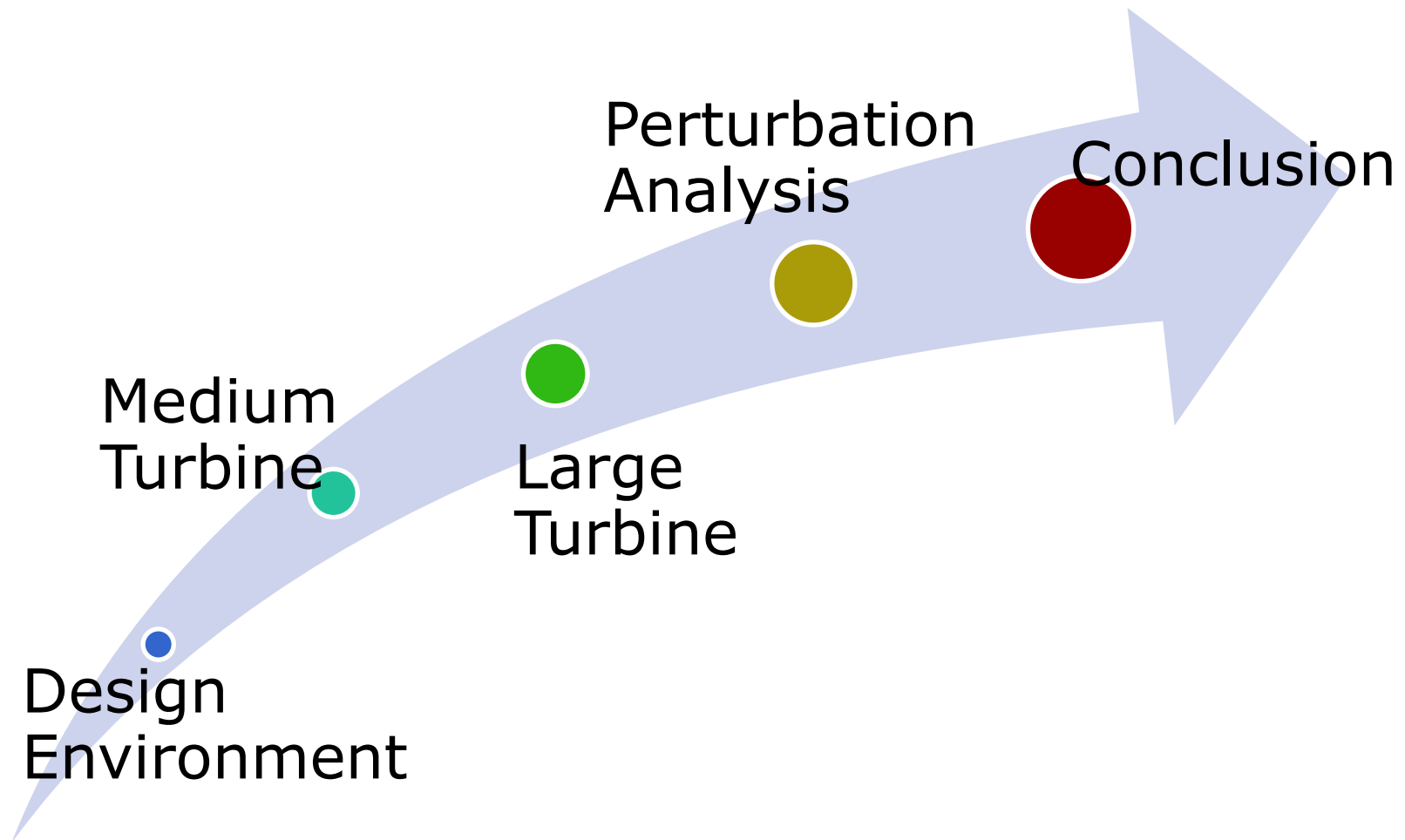


# Problematic

Design difficulty		Water depth	
		shallow	deep
Turbine size	small	mild	medium
	large	medium	high

**Is the design of large diameter monopile placed at deep waters a straightforward extrapolation process from mild or medium designs?**

# Agenda



# Design Environment

**Site Conditions**: Metocean conditions and soil properties are presented in the paper.

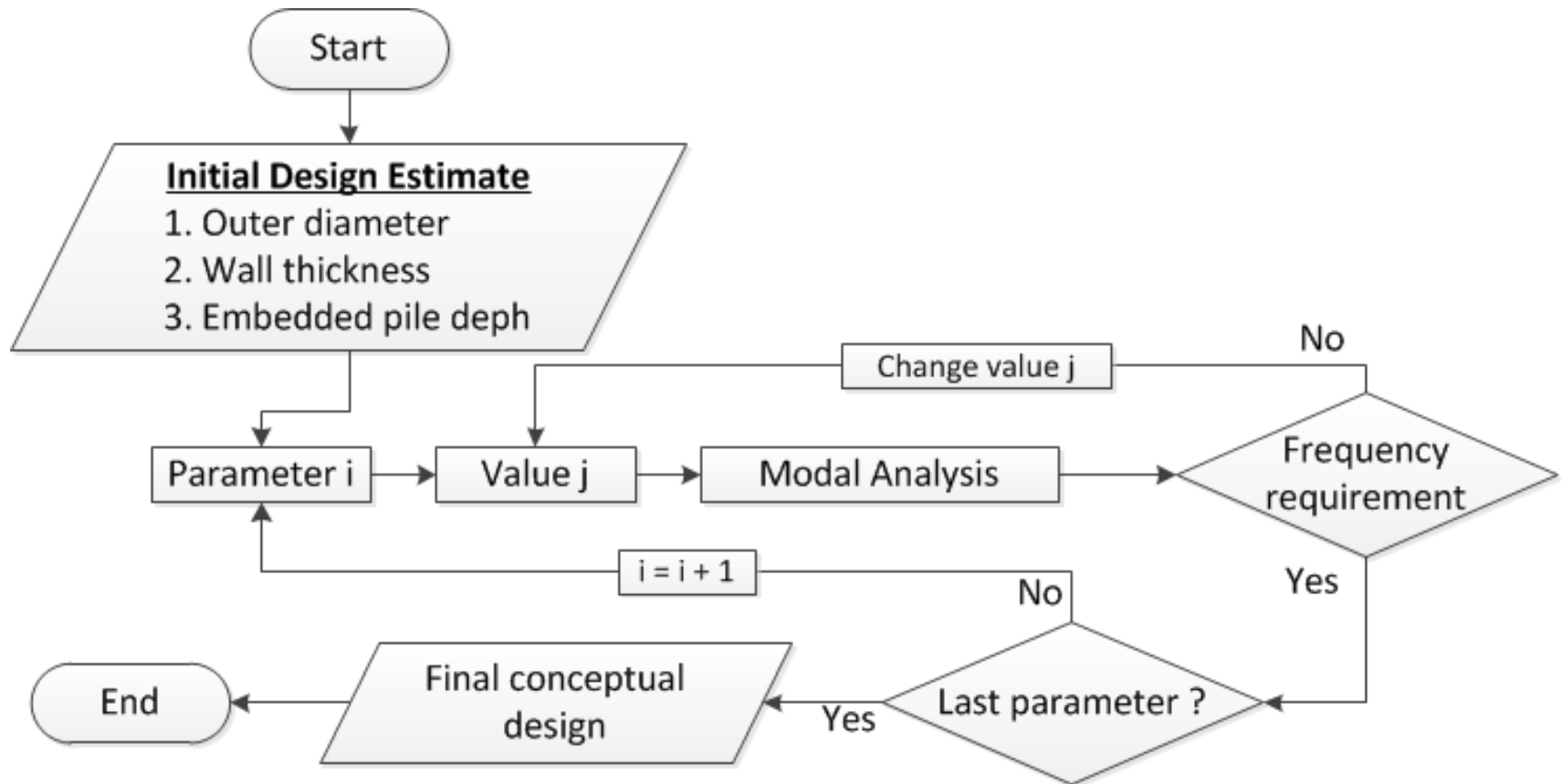
**Structure**: DTU 10 MW RWT

**Design Constraints**:

- Conflicting aspects: manufacturing, mass, wave loading
- Natural frequencies
- Maximum outer diameter 10.0 m
- Minimum wall thickness
- Maximum displacement at mudline and toe
- Soil plastification

**Computer software**: aero-hydro-servo-elastic package, HAWC2

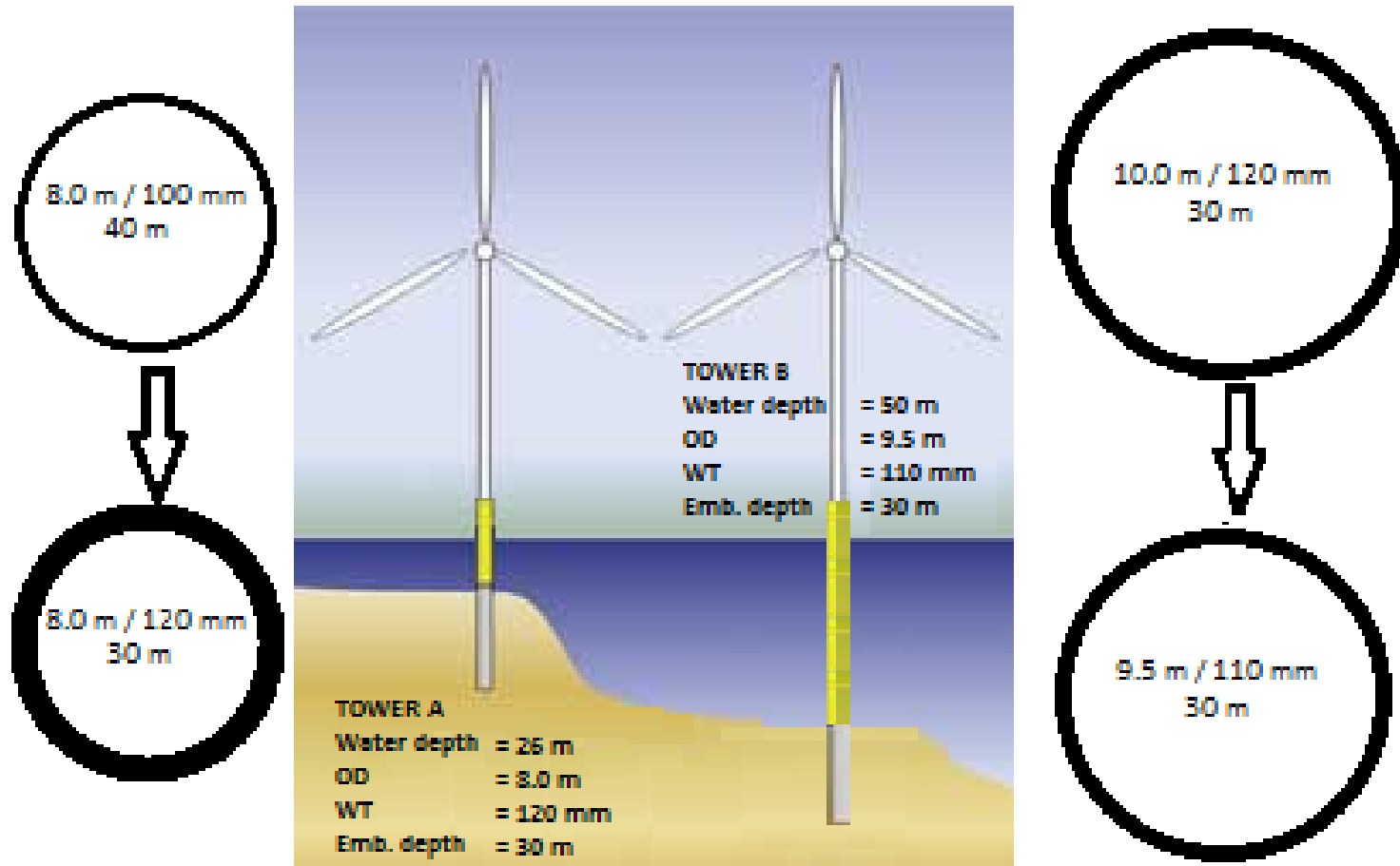
# Geometry Design Process



# Specificity of large diameter monopile

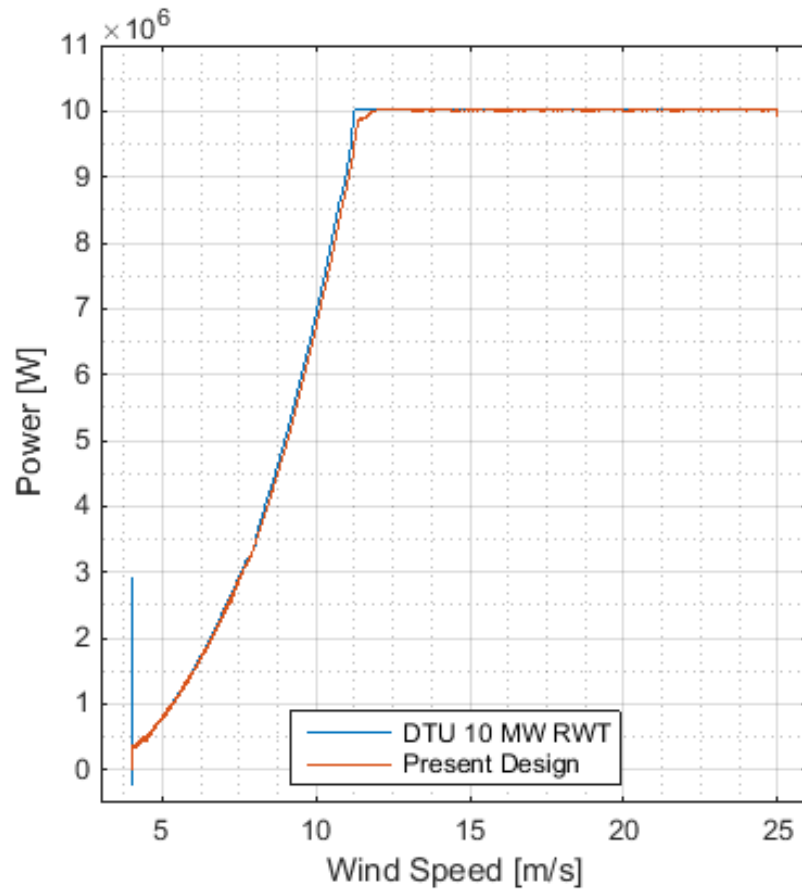
- Structural stiffness distribution
- Influence of wave diffraction
- Soil-structure interaction

# Geometry design

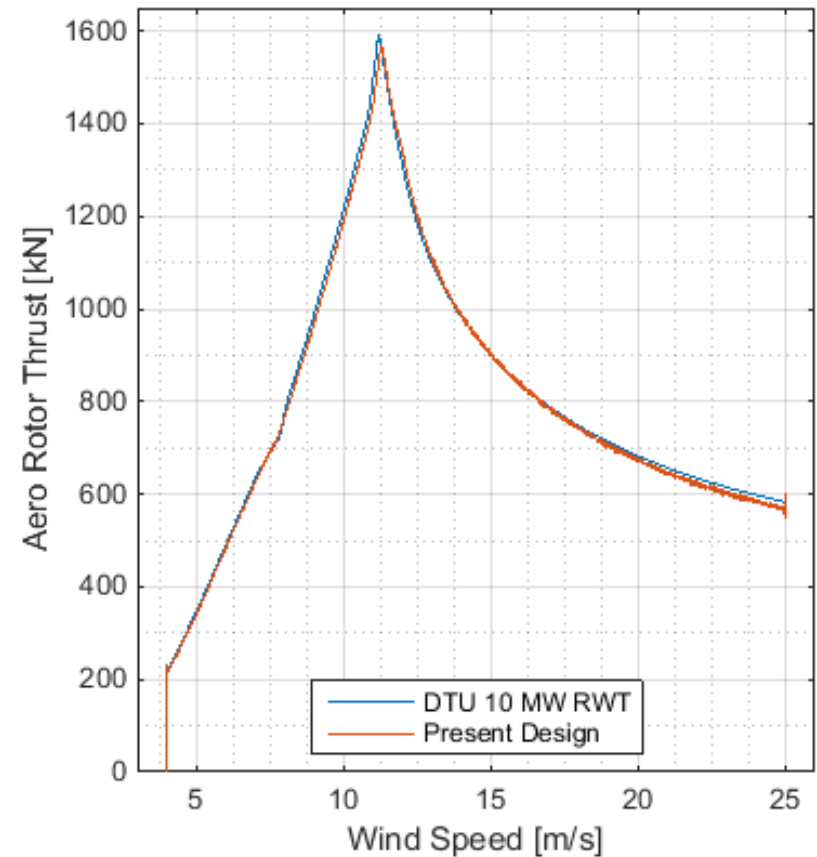




# Global Performance



Power curve

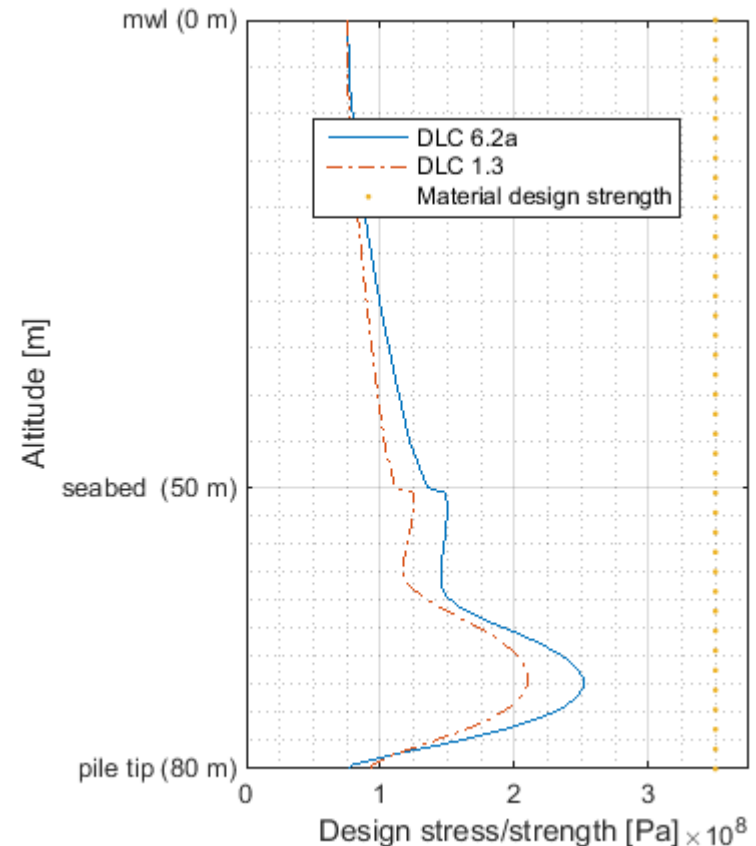


Aero rotor thrust curve

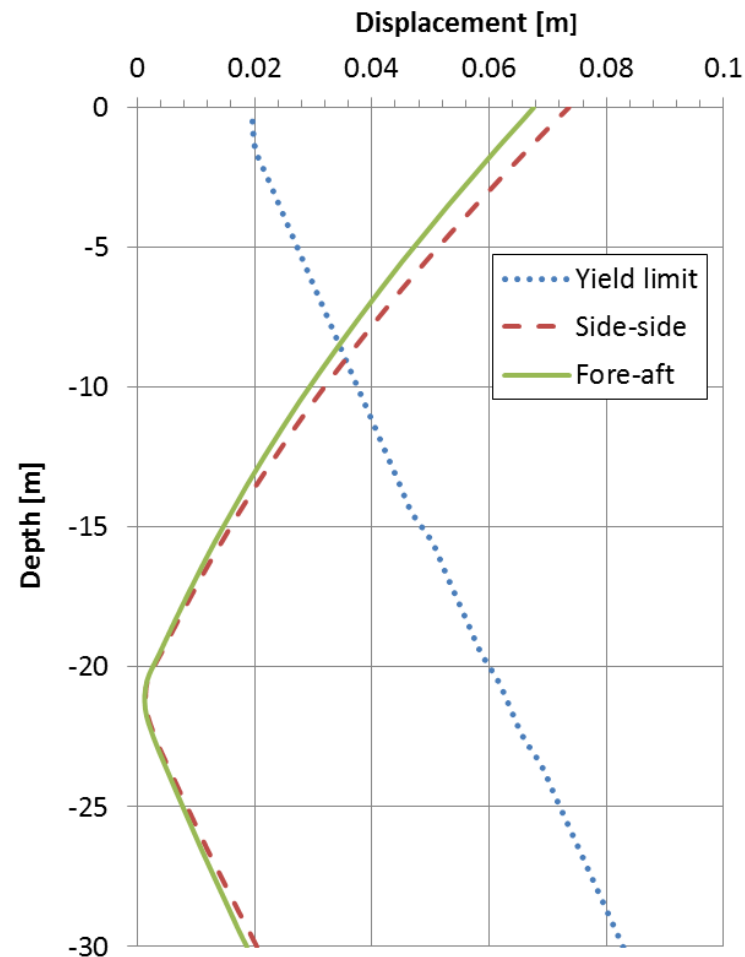
# Ultimate Limit state: Load cases and Stress vs strength

**DLC 1.3:** Ultimate loading resulting from extreme turbulence conditions with normal sea states.

**DLC 6.2a:** Ultimate loading resulting from turbulent extreme wind model with extreme sea states, coupled with loss of electrical power.



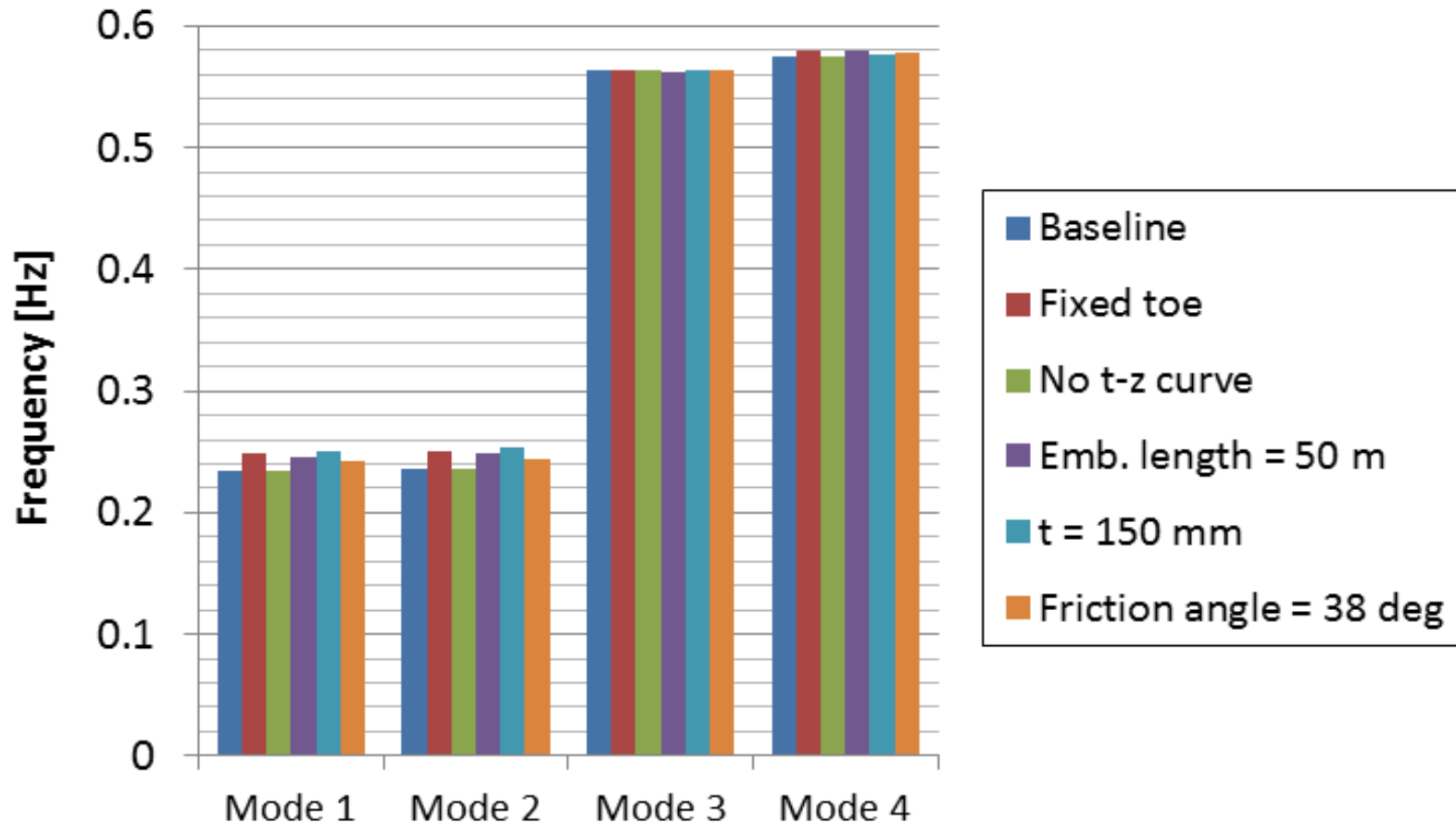
# Ultimate Limit state: soil plasticization



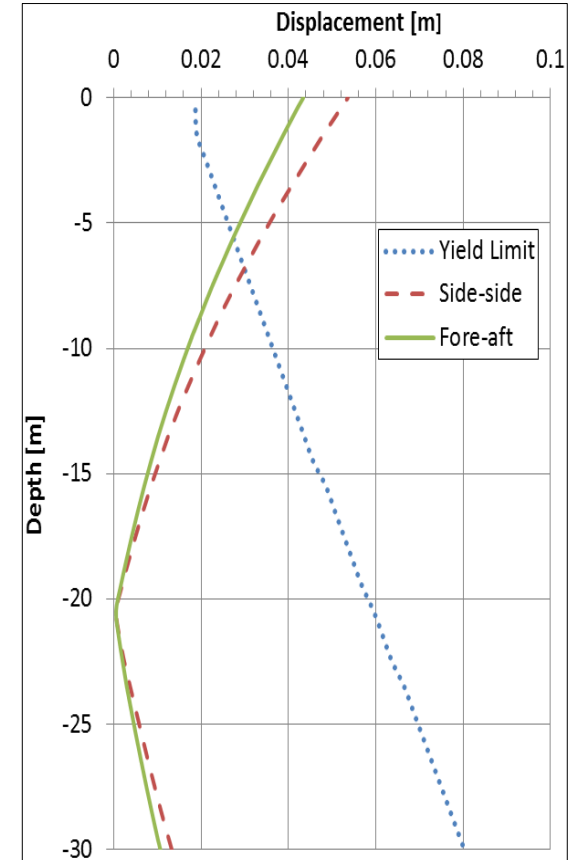
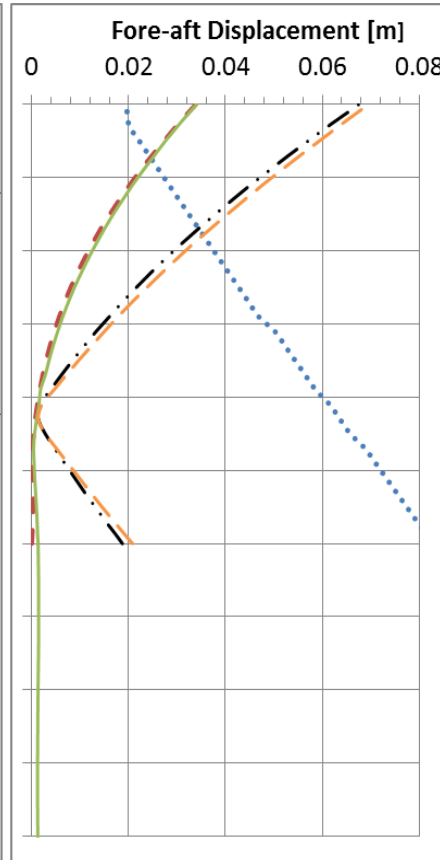
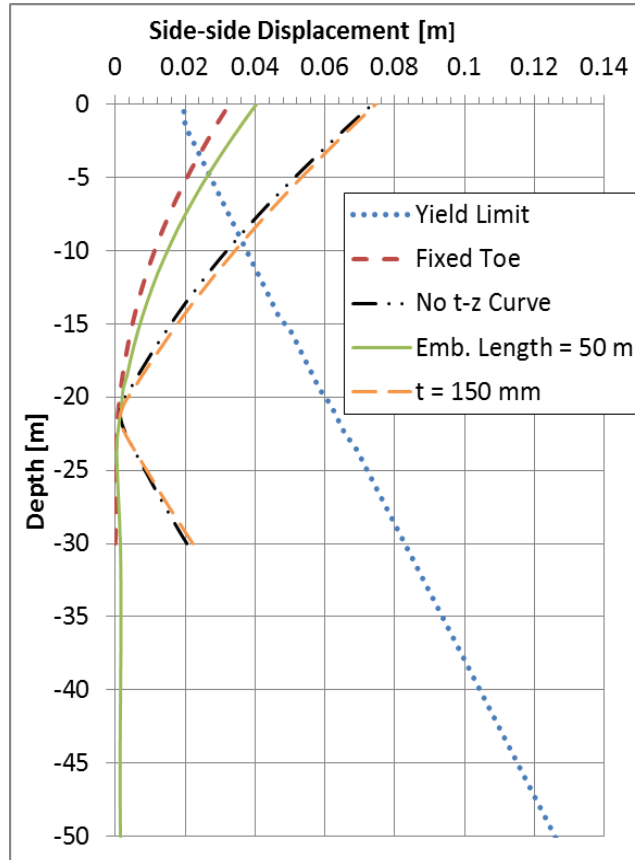
# Perturbation Analysis: Definition

- **Baseline** – Toe as joint with restrained yaw and vertical motions. Contribution of axial skin friction. Wall thickness: 110 mm. Embedded depth: 30 m. Soil internal friction angle:  $35^\circ$ .
- Perturbation A – **Toe boundary condition**. The pile tip is fixed, i.e. all degrees of freedom are restrained.
- Perturbation B – **Axial skin friction contribution**. The contribution of skin friction to the pile axial equilibrium has been annihilated.
- Perturbation C – **Deeper pile**. The embedded length of the pile has been changed from 30 m to 50 m.
- Perturbation D – **Thicker wall**. The wall thickness has been increased to 150 mm.
- Perturbation E – **Soil friction angle**. The soil around the pile is set denser; its internal angle has been improved from  $35^\circ$  to  $38^\circ$ .

# Perturbation Analysis: Dynamic stiffness



# Perturbation Analysis: Deflection and plastic zone



Perturb. A, B, C, D

Perturb. E

# Perturbation Analysis: Bill of material

Case	Baseline	A, B, E	C	D
<b>Mass [t]</b>	2700	2700	3210	3666
<b>Rel. diff. [%]</b>	-	0.00	18.87	35.78

# Perturbation Analysis: Ultimate loads

At the interface

	<b>Fres [kN]</b>	<b>Fz [kN]</b>	<b>Mres [kNm]</b>	<b>Mz [kNm]</b>
<b>Baseline</b>	3500	13000	290000	-38000
<b>Pert. A</b>	0.0%	0.0%	3.4%	36.8%
<b>Pert. B</b>	0.0%	0.0%	0.0%	-234.2%
<b>Pert. C</b>	-2.9%	7.7%	-3.4%	-415.8%
<b>Pert. D</b>	-2.9%	0.0%	3.4%	-218.4%
<b>Pert. E</b>	2.9%	0.0%	3.4%	36.8%

At the mudline

	<b>Fres [kN]</b>	<b>Fz [kN]</b>	<b>Mres [kNm]</b>	<b>Mz [kNm]</b>
<b>Baseline</b>	11000	40000	730000	-38000
<b>Pert. A</b>	0.0%	0.0%	2.7%	39.5%
<b>Pert. B</b>	9.1%	0.0%	0.0%	-236.8%
<b>Pert. C</b>	9.1%	0.0%	8.2%	-442.1%
<b>Pert. D</b>	0.0%	17.5%	2.7%	-221.1%
<b>Pert. E</b>	9.1%	0.0%	5.5%	39.5%



# Discussion

- Similar dynamic stiffness but different lateral deformations
- Increase wall thickness is inefficient
- Axial skin friction is non-influential
- Fixed toe may be misrepresentative

# Conclusion

- Distribute flexural stiffness along the whole length – Tower Change.
- Start with the traditional procedure, and progressively adjust the design parameters.
- Target the centre of the soft-stiff range – resulting lateral deformations will be moderate.
- Mind the soil status – consider monopile deepening.

**THANK YOU  
FOR YOUR ATTENTION**

# Medium size turbine

## Initial design estimate:

- Outer diameter 8.0 m
- Wall thickness 100 mm
- Embedded part 50.0 m

## Final design:

- 8.0 m
- 120 mm
- 30.0 m

Wall thickness [mm]	Eigen frequencies [Hz]			
	Mode 1	Mode 2	Mode 3	Mode 4
90	0.224	0.227	0.544	0.584
100	0.229	0.232	0.545	0.584
<b>120</b>	<b>0.238</b>	<b>0.242</b>	<b>0.546</b>	<b>0.585</b>

Embedded length [m]	Eigen frequencies [Hz]			
	Mode 1	Mode 2	Mode 3	Mode 4
25.00	0.218	0.221	0.548	0.580
<b>30.00</b>	<b>0.227</b>	<b>0.230</b>	<b>0.548</b>	<b>0.587</b>
50.00	0.238	0.242	0.546	0.585

# Geometry design

## Initial design estimate:

- Outer diameter 10.0 m
- Wall thickness 120 mm
- Embedded part 30.0 m

## Final design:

- 9.5 m
- 110 mm
- 30.0 m

Outer diameter [m]	Eigen frequencies [Hz]			
	Mode 1	Mode 2	Mode 3	Mode 4
<b>9.50</b>	<b>0.218</b>	<b>0.267</b>	<b>0.548</b>	<b>0.564</b>
10.00	0.225	0.227	0.549	0.565

Tower type and mass [t]	Eigen frequencies [Hz]			
	Mode 1	Mode 2	Mode 3	Mode 4
A: 426.293	0.218	0.267	0.548	0.564
<b>B: 511.131</b>	<b>0.239</b>	<b>0.241</b>	<b>0.563</b>	<b>0.576</b>

Wall thickness [mm]	Eigen frequencies [Hz]			
	Mode 1	Mode 2	Mode 3	Mode 4
<b>110</b>	<b>0.234</b>	<b>0.236</b>	<b>0.563</b>	<b>0.575</b>
120	0.239	0.241	0.563	0.576

# Conclusion

